Effect of CP violating phases on neutral Higgs boson phenomenology in the MSSM

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ABSTRACT

In the MSSM with complex SUSY parameters we consider a specific case where the second heaviest Higgs boson H_2 is SM like, while H_1 and H_3 are both strongly mixed states of CP odd and CP even scalar fields. Such a scenario could be probed at a Linear Collider via the mechanism $e^+e^- \to H_1 H_3$.

1. Introduction

The numerous parameters of the MSSM allow for additional CP violating phases beyond that of the Standard Model CKM phase. A phenomenological consequence of complex SUSY parameters is "scalar-pseudoscalar mixing" [1], where the neutral Higgs boson mass eigenstates are linear combinations of both the scalar (CP even) and pseudoscalar (CP odd) fields. The $3X3$ neutral Higgs boson mass squared matrix M_N^2 takes the following form:

$$M_N^2 = \begin{pmatrix} M_S^2 & M_{PS}^2 \\ M_{PS}^2 & M_P^2 \end{pmatrix} \tag{1}$$

where M_S^2 (M_P^2) denotes the 2X2 (1X1) submatrix for the pure CP even (CP odd) entries, while M_{PS}^2 mixes the CP odd and CP even scalar fields. In the MSSM, M_{PS}^2 is induced at the 1-loop level and is explicitly given by [2]:

$$M_{PS}^2 = \Big(\frac{m_t^4}{v^2} \frac{|\mu||A_t|}{32\pi^2 M_{SUSY}^2} \Big) \sin\phi_{CP} \times f(M_{SUSY}, A_t, \mu, \tan\beta) \tag{2}$$

Here $\phi_{CP} = arg(A_t\mu)$, and f is a dimensionless function of several SUSY parameters. Setting $\phi_{CP} = 0$ ensures $M_{PS}^2 = 0$, resulting in Higgs mass eigenstates with definite CP quantum numbers. In order to have appreciable mixing ($M_{PS} \approx M_Z$) one requires i) Large $|\mu|/M_{SUSY}$ and/or large $|A_t|/M_{SUSY}$, and ii) moderate to large $\sin\phi_{CP}$.

It is known that $\sin\phi_{CP}$ is strongly constrained by fermion Electric Dipole Moments (EDMs) if the SUSY spectrum is relatively light, $M_{SUSY} < 1000$ GeV. However, the EDMs and M_{PS} exhibit different dependences on M_{SUSY}, provided that the ratios $|\mu|/M_{SUSY}$ and $|A_t|/M_{SUSY}$ are kept fixed [3]. This is displayed in Fig. 1 where the CP odd component (O_{31}) of H_1 shows little sensitivity to M_{SUSY} and can be maximal for large phase, while the neutron and electron EDMs show a $\sim 1/M_{SUSY}^2$ dependence.

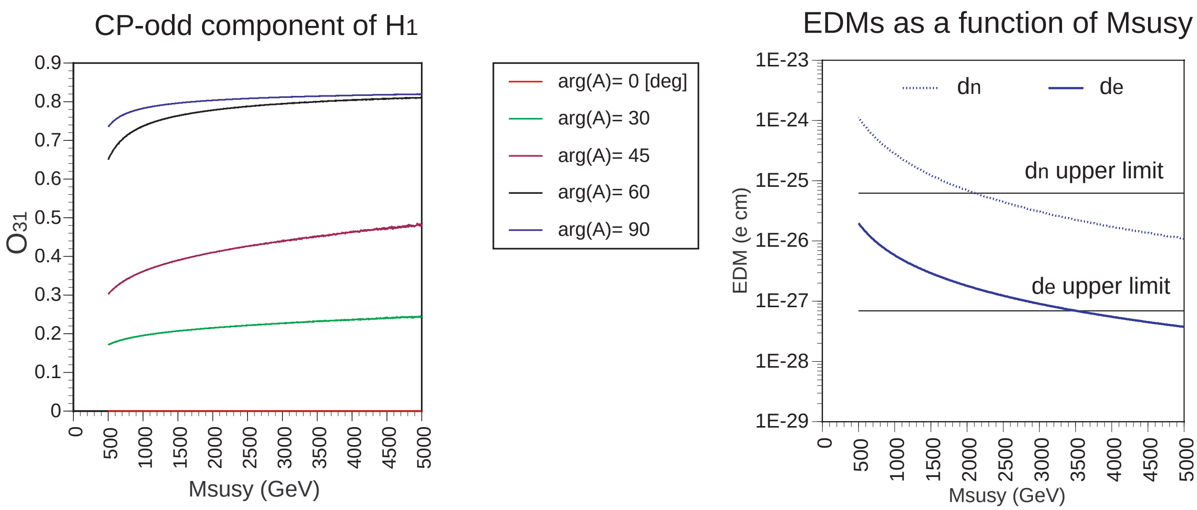

Figure 1: Left figure: CP odd composition (O_{31}) of the lightest Higgs eigenstate H_1 for various arg(A_t) as a function of M_{SUSY}; Right figure: Electron and Neutron EDMs for arg($A_t = 90°$) as a function of M_{SUSY}.

2. Numerical Results

We consider a benchmark scenario which gives rise to a phenomenologically interesting case of strong scalar-pseudoscalar mixing which is also compatible with the aforementioned EDM constraints.

$$\begin{gathered} M_{SUSY} = 3000\, GeV, \ \tan\beta = 7 \\ |\mu/M_{SUSY}| = 10, \ |A_t/M_{SUSY}| = 1.5, \ \phi_{CP} = \pi/2 \end{gathered} \tag{3}$$

We work in a rotated basis in which only one of the $SU(2)XU(1)$ Higgs doublets possesses a vacuum expectation value, whose corresponding neutral CP even Higgs boson is given by h_{SM}. In this basis H_i are as follows:

$$H_i = O_{1i}H + O_{2i}h_{SM} + O_{3i}A \tag{4}$$

In Fig. 2 we show the composition (O_{ji}) of H_i as a function of $m_{H^\pm}$. For $m_{H^\pm} < 200$ GeV, H_2 is SM like and is responsible for breaking the $SU(2)XU(1)$ symmetry (see [4] for the analogous scenario with smaller M_{SUSY}), while H_1 and H_3 are strongly mixed states of H and A. For $m_{H^\pm} > 200$ GeV, one finds the usual decoupling behaviour where H_1 becomes SM like, but the two heavier states H_2 and H_3 are strongly mixed states of H and A [2]. The large mixing for $m_{H^\pm} < 200$ GeV occurs because the mass matrix elements for $H - H, A - A$ and $A - H$ transitions are relatively large and form a 2X2 submatrix whose entries are roughly equal in magnitude. The mass matrix elements for $h_{SM} - A$ and $h_{SM} - H$ are considerably smaller, giving rise to an eigenstate H_2 which is almost purely h_{SM}. For $m_{H^\pm} > 200$ GeV, the heavy Higgs $2X2$ submatrix for $A - A, A - H$ and $H - H$

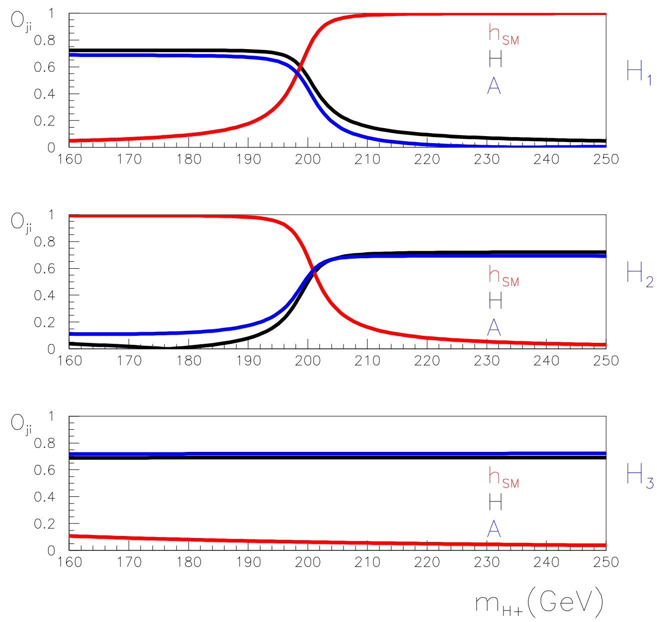

Figure 2: O_{ji} as a function of $m_{H^\pm}$, for H_1, H_2, H_3.

decouples from the SM like H_1. The magnitude of the $A-H$ entry is roughly equal to the difference of the diagonal terms, leading to eigenstates which are mixed states of CP.

In Fig. 3(left plots) we show $\sigma(e^+e^- \to H_iZ, H_iH_j)$ as a function of $m_{H^\pm}$, at a Linear Collider of $\sqrt{s} = 500$ GeV. For $m_{H^\pm} < 200$ GeV, $\sigma(e^+e^- \to H_2Z)$ is SM like and thus H_2 would be found at the LHC. Detection of H_1 and H_3 might be difficult at the LHC, but $e^+e^- \to H_1H_3$ would offer sizeable rates at a Linear Collider and is a potentially effective probe of the scalar-pseudoscalar mixing. Note the large mass splitting $M_{H_3} - M_{H_1}$ for $M_{H^\pm} < 200$ GeV, a consequence of the form of the 2X2 submatrix for the $H-H$, $A-A$, $A-H$ entries. Finally, Fig. 3 (right plot) shows contours of $\sigma_R = \sigma(e^+e^- \to ZH_2)/\sigma(e^+e^- \to ZH_1)$ in the plane $(m_{H^\pm}, \tan\beta)$. In a sizeable region $\sigma_R > 10$, and thus H_2 is SM like.

3. Acknowledgements

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4. References

[1] A. Pilaftsis, *Phys. Lett.*B435, 88 (1998); D. A. Demir, *Phys. Rev.*D60, 055006 (1999); S. Y. Choi, M. Drees and J. S. Lee, *Phys. Lett.*B481, 57 (2000); T. Ibrahim and P. Nath, *Phys. Rev.*D63, 035009 (2001); S. Y. Choi, K. Hagiwara and J. S. Lee, *Phys. Rev.*D64, 032004 (2001); A. G. Akeroyd and A. Arhrib, *Phys. Rev.*D64, 095018 (2001); F. Borzumati, J. S. Lee and W. Y. Song, *Phys. Lett.*B595, 347 (2004); R. M. Godbole, S. Kraml, M. Krawczyk, D. J. Miller, P. Niezurawski

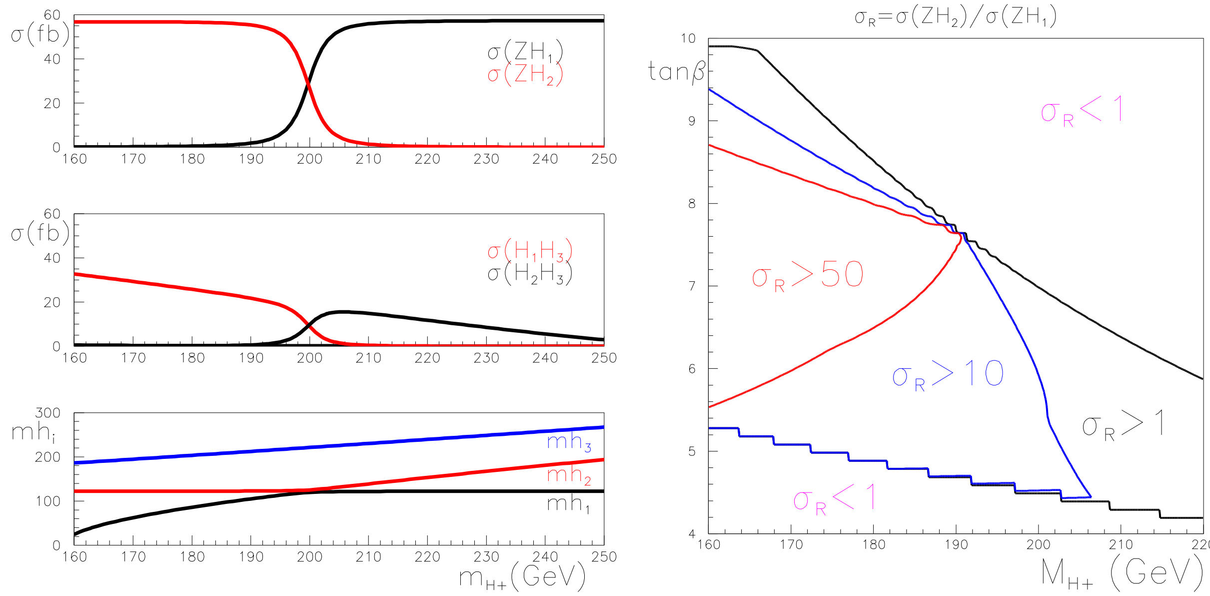

Figure 3: Left figure: $\sigma(e^+e^- \to H_i Z)$ (upper), $\sigma(e^+e^- \to H_i H_j)$ (middle) and m_{H_i} (lower) as a function of $m_{H^\pm}$. Right figure: $\sigma_R = \sigma(e^+e^- \to ZH_2)/\sigma(e^+e^- \to ZH_1)$ in the plane $(m_{H^\pm}, \tan\beta)$

and A. F. Zarnecki, arXiv:hep-ph/0404024; J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. **156**, 283 (2004)

[2] A. Pilaftsis and C. E. M. Wagner, *Nucl. Phys.* **B553**, 3 (1999).

[3] T. Ibrahim, *Phys. Rev.* **D64**, 035009 (2001).

[4] M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, *Phys. Lett.* **B495**, 155 (2000); M. Carena, J. R. Ellis, S. Mrenna, A. Pilaftsis and C. E. M. Wagner, *Nucl. Phys.* **B659**, 145 (2003).